Detection and identification of phase and frequency drifts in clock ensembles

Christian Trainotti and Gabriele Giorgi
Institute for Communications and Navigation, German Aerospace Center (DLR), Germany

A stable system time scale is a fundamental part of Global Navigation Satellite Systems (GNSSs). A degradation of the time scale directly impacts the quality of positioning and time dissemination services offered by the system. The continuity of these services is vital, making the robustness of time generation a paramount aspect that has to be ensured and monitored.
The composite clock approach provides a method for the generation of a time scale that is inherently stable and robust. Instead of relying on a single clock signal, the measurements of a set of clocks are used. A Kalman filter processes these measurements, allowing the generation of a weighted average, the so-called Implicit Ensemble Mean (IEM) [1]. Timing facilities, navigation satellites, and future GNSSs are potential application with high stability requirements, in which the improved stability and enhanced robustness of the IEM could play an influential role. However, the IEM realization can still be impacted by failures in single clocks. By employing Fault Detection and Identification (FDI) techniques, dedicated statistical tests can be constructed, aiming to detect and identify these faults. For instance, it is possible to detect phase jumps in the signal of one clock by means of a snapshot test, which checks for blunders in the predicted-minus-observed phase residuals of the Kalman filter. Slow deviations from the clocks' nominal behavior such as phase drifts can be revealed by a batch test. This makes use of a sliding window to compute the overlapping Allan deviation (OADEV) of the signals and compare it to a nominal model. These methods were introduced and tested in a previous work by the authors [2]. The aim of the present paper is to extend the analyses by focusing on the fault detection and identification of different types of clock drifts.

Three specific drift scenarios are examined in this paper. The first case involves a linear phase drift caused by a frequency step in one clock. Secondly, a linear frequency drift (quadratic phase drift) is considered. Finally, an oscillating frequency behavior is assumed. The latter case intends to simulate e.g. orbital effects on satellites' clocks or effects due to daily temperature fluctuations.
By using these cases as examples, the performance of the proposed FDI method is analyzed as function of various settings and parameters. First, different measurement topologies are tested. In the previous work, one clock in the ensemble was acting as an internal reference, to which all other units were measured. This introduces an ambiguity, since a fault in the reference unit cannot be distinguished from a simultaneous fault in different clocks. Now, a closed loop ring structure is considered, where the clocks are pairwise measured. This reduces the ambiguity when locating the fault source and eases the identification step. Second, test parameters are varied, such as the length of the sliding window and the sampling interval for which the OADEV is computed. Their influence on the test performance is assessed, so that a suitable value can be chosen depending on the failure mode the test aims to detect. The Minimum Detectable Biases (MDB) are then derived for each of the tests developed. The MDBs describe the smallest fault magnitude that the detector is able to reveal, given the integrity requirements and the particular scenario. In this way, it is possible to estimate the relation between the number of clocks in the ensemble, the MDBs, and the integrity demands for the three different fault cases. Finally, the system level effects caused by an undetected fault are analyzed. The influence on the IEM generation is assessed in terms of OADEV as function of the number of clocks in the ensemble.

These three scenarios are reproduced in simulation and in hardware in the DLR's TimeLab. A dedicated ensembling algorithm combines the measurements of three cesium frequency references and it is equipped with the statistical tests for fault detection and identification. A given phase profile reproducing a drift is injected in the signal of one of the clocks by means of a High Resolution Offset Generator, so that the test algorithm can be assessed with a controlled fault pattern. In parallel, the same ensemble setup and fault scenario are simulated in software, providing a comparison for the hardware results.

This work is supported by the Helmholtz-Gemeinschaft Deutscher Forschungszentren e.V. under grant number ZT-0007 (ADVANTAGE, Advanced Technologies for Navigation and Geodesy).

[1] K. R. Brown Jr., "The theory of the GPS composite clock," in *Proceedings of the 4th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GPS)*, (Albuquerque, NM,USA), pp. 223–242, ION, ION, 199.
[2] C.Trainotti, G. Giorgi, and J. Furthner, "Detection and Identification of Faults in Clock Ensembles". *Paper presented at ION GNSS+ 2019*, September 2019, Miami, FL, USA.